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THERMOACOUSTIC HEAT TRANSPORT

ANTHONY A. ATCHLEY

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This annual report details progress in basic research in thermoacoustic heat transport, made during the period February 1 through September 30, 1989. The approach and progress of three projects are discussed. The first project involves measurements of thermoacoustic phenomena using thermoacoustics couples (TACs). The second is an investigation of heat driven prime movers and heat pumps. The purpose of the third project is to examine means of visualizing thermoacoustic processes. A publications, patents, presentations, and honors report is also included. Keywords;

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ABSTRACT

This annual report details progress in basic research in thermoacoustic heat transport made during the period February 1 through September 30, 1989. The approach and progress of three projects are discussed. The first project involves measurements of thermoacoustic phenomena using thermoacoustic couples (TACs). The second is an investigation of heat driven prime movers and heat pumps. The purpose of the third project is to examine means of visualizing thermoacoustic processes. A publications, patents, presentations, and honors report is also included.

A. PROJECT DESCRIPTION

This project involves basic research in thermoacoustic heat transport. The objectives of the project are the investigation of thermoacoustic phenomena in very high amplitude acoustic standing waves using thermoacoustic couples (TAC's), investigation of heat driven thermoacoustic prime movers and heat pumps, and investigation of methods to "visualize" thermoacoustic phenomena, in particular, the evolution of temperature gradients in objects subjected to an acoustic standing wave.

The premise of this basic thermoacoustics research can be summarized as follows. While early measurements of thermoacoustic phenomena qualitatively agree quite well with the theory developed by Wheatley[1] and Swift,[2] there have been few thorough, quantitative comparisons of measurement and theory. The quantitative studies that have been performed indicate that the theory does not adequately explain the results.[3-7] We have undertaken a series of quantitative investigations using a variety of thermoacoustic devices in order to understand the reasons for the shortcomings of the theory. A description of these investigations follows.

B. APPROACH AND PROGRESS

Thermoacoustic phenomena and the associated devices can be described in terms of two basic modes of operation, heat pumps and prime movers. In thermoacoustic heat pumps, an acoustic field stimulates the transport of entropy over the surface of an object, resulting in a thermal gradient being established across that object. In prime movers, a thermal gradient is established across an object which is part of, or housed in, a resonant enclosure. At sufficiently high gradients, sound is spontaneously generated in the resonator. The thermal energy stored in the gradient is converted in to acoustic energy; the work output of the device is equal to the energy in the acoustic field. Our study of thermoacoustic processes involves investigating both of these fundamental classes of phenomena.

1. Thermoacoustic Couple (TAC) Measurements

The purpose of the TAC measurements is to perform a thorough investigation of basic thermoacoustic phenomena using the simplest class of thermoacoustic engine. A

typical TAC is composed of a stack of short (compared to the acoustic wavelength), poorly thermally conducting plates, spaced by at least a few thermal (and viscous) penetration depths. The advantage of using a TAC is that its design allows assumptions to be made which reduce the theory of thermoacoustic heat transport to its simplest form. The TAC measurements generally involve measuring the temperature difference developed across a TAC as a function of the position of the TAC in an acoustic standing wave. T' e results are compared to predictions based on the work of Wheatley et al.[1] Our previous research[4-7] has shown that the theory agrees relatively well with the result of measurements made at low acoustic intensities. However, there is serious disagreement between theory and experiment at higher acoustic intensities. The disagreement is worse in regions of high acoustic particle speed.

A major effort in FY 89 has been to develop a computer controlled apparatus to facilitate data acquisition.[6,7] An extensive set of measurements has been made with this apparatus,[8] which allows us to vary the acoustic pressure amplitude, the position of the TAC, the acoustic frequency, and the mean gas pressure. These measurements represent one of the most complete studies of thermoacoustic phenomena to date. A discussion of some of these results follow.

Figure 1 illustrates the comparison between the measured temperature difference across the TAC (solid curve) and the theoretical temperature difference (dashed curve) for a drive ratio of 0.28%. (The drive ratio is defined as the ratio of the acoustic pressure amplitude to the mean gas pressure.) The theoretical temperature difference is computed using Eq. (17) of Ref. 1. The TAC is composed of a stack of five 6.85 mm long, 25.3 mm wide plates spaced by 1.52 mm. The individual plates are laminates of 0.0889 mm thick 302 stainless steel shim stock and 0.1016 mm thick G10 fiberglass sheet epoxied together. The center plate of the stack is instrumented with a thermopile composed of 5 Type E, chromel-constantan, thermocouples which allow measurement of the temperature difference across the TAC. The thermopile is sandwiched between the stainless steel and fiberglass plates. In Fig. 1, the temperature differences are plotted as functions of kx, where k is the wave number and x is the distance of the center of the TAC from the rigid end of the standing wave tube. The positions of the particle velocity and pressure antinodes are indicated on the graph. As seen in the figure, the overall comparison is good, though the maximum measured temperature difference is approximately 20% larger than the predicted result. We attribute this discrepancy to an uncertainty in the thermal conductivity of the materials used to construct the TAC, and the fact that measurements taken with TACs of essentially the same design give slightly different results. In general, however, the measured and predicted results are in reasonably good agreement at low drive ratios.

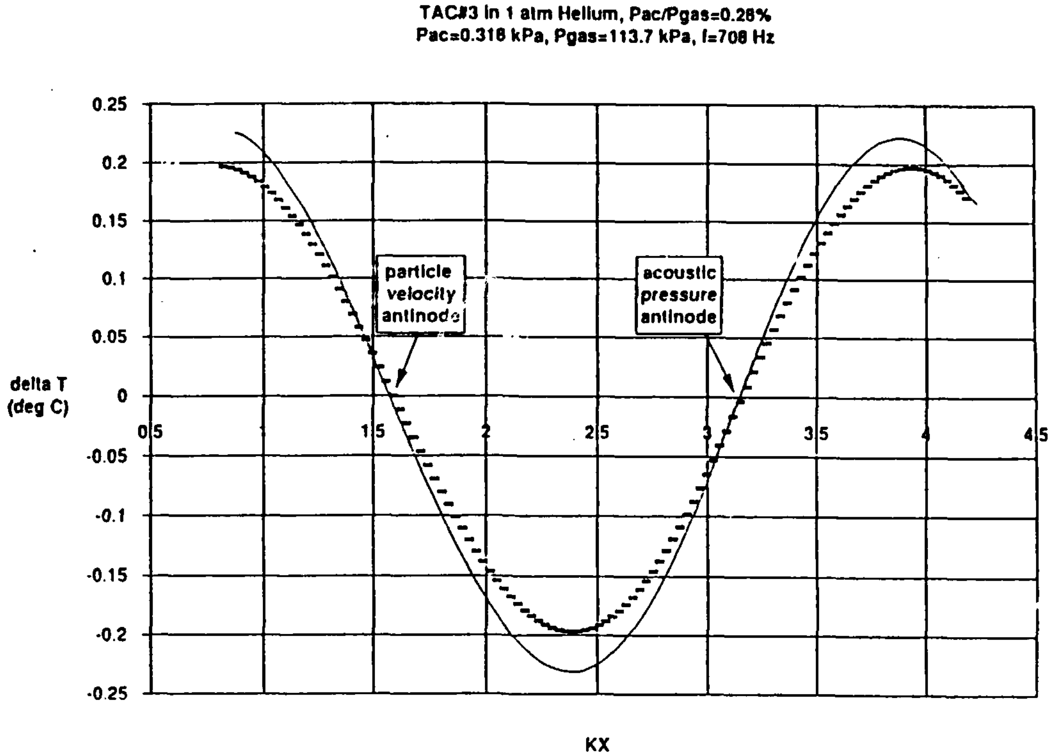

Figure 1

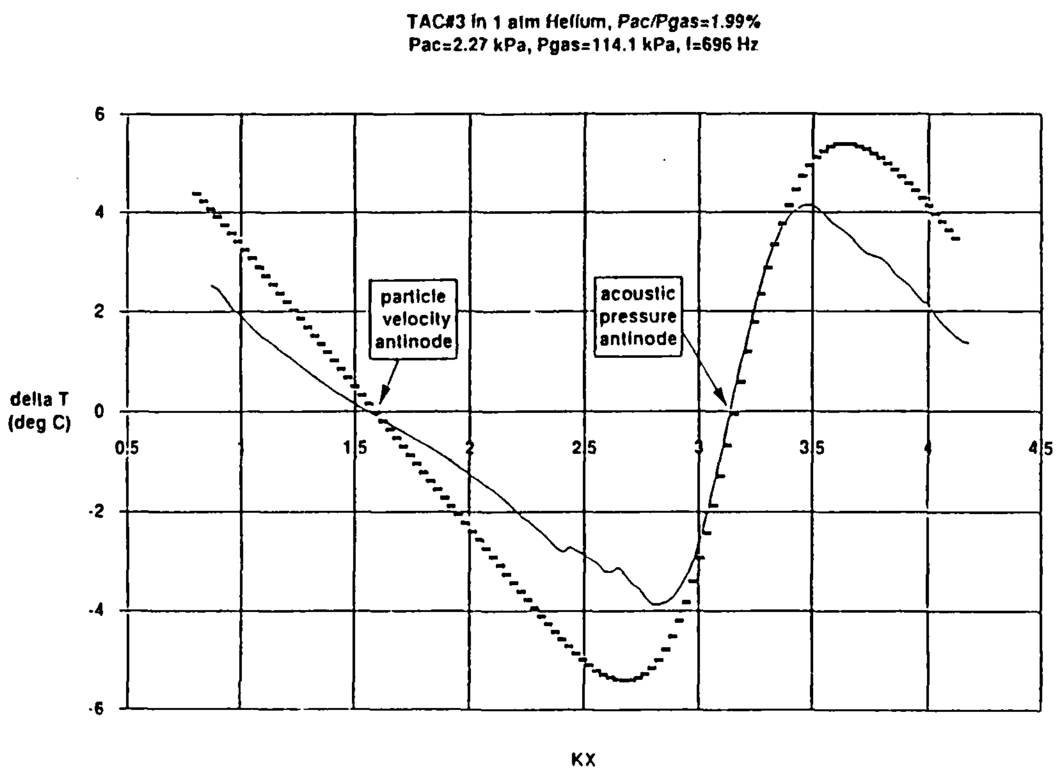

Figure 2

Figure 2 illustrates the effect of increasing the drive ratio to 1.99%. Four areas for comparisons are obvious. First, the agreement is quite good in the vicinity of the pressure antinode. The slopes of the measured and predicted temperature differences are approximately equal. Secondly, the agreement in the vicinity of the velocity antinode is poor. The slope of the measured temperature difference is much less than that of the predicted result. Third, the data series (or "waveform") of the measured temperature difference is quite irregular and jagged in the vicinity of the maximum temperature difference. Finally, the measured maximum temperature difference is significantly less and occurs at a different position than the predicted maximum. In short, the agreement between theory and experiment is poor at high drive ratios except near the pressure antinode.

Figure 3 illustrates the theoretical temperature difference as a function of kx for drive ratios from 0.17 to 1.99%. (The individual values of the drive ratio have been omitted, in order to reduce clutter on the graph. The data presented in Figs. 1 and 2 are a subset of these data.) This graph clearly indicates the progression from a sinusoid to a sawtooth curve and the displacement of the maximum temperature difference toward the pressure antinode as described by Wheatley et al.[1] The actual temperature differences are shown in Fig. 4 for the same experimental conditions. The measurements do confirm qualitatively the sinusoid-to-sawtooth progression. One of the curves is dashed to demarcate two regions of behavior. The curves between the kx axis and this curve are smooth and regular. The curves on the other side of the dashed curve become jagged and irregular. This transition occurs in all of the data sets we have taken.

In order to quantify the comparison of these two figures, three ratios will be examined. The first ratio is that of the experimental slope of the temperature difference curve in the vicinity of the velocity antinode to the theoretical slope in the vicinity of the velocity antinode. The second ratio is that of the experimental to theoretical slope in the vicinity of the pressure antinode. The final ratio is that of the maximum experimental temperature difference to the maximum theoretical temperature difference. As seen in Fig. 4, the temperature difference reaches a maximum on both sides of the pressure antinode, so two values of the maximum temperature difference ratio can be computed. These ratios are plotted as functions of the drive ratio (in %) in Fig. 5 for the data presented in Figs. 3 and 4. The data corresponding to the slope ratio in the vicinity of the velocity antinode are labeled "SOVmax", while those corresponding to the slope ratio in the vicinity of the pressure antinode are labeled "SOPmax." The maximum temperature difference ratio data for the temperature maximum to the left of the pressure antinode is labeled "1st", while the one to the right is labeled "2nd".

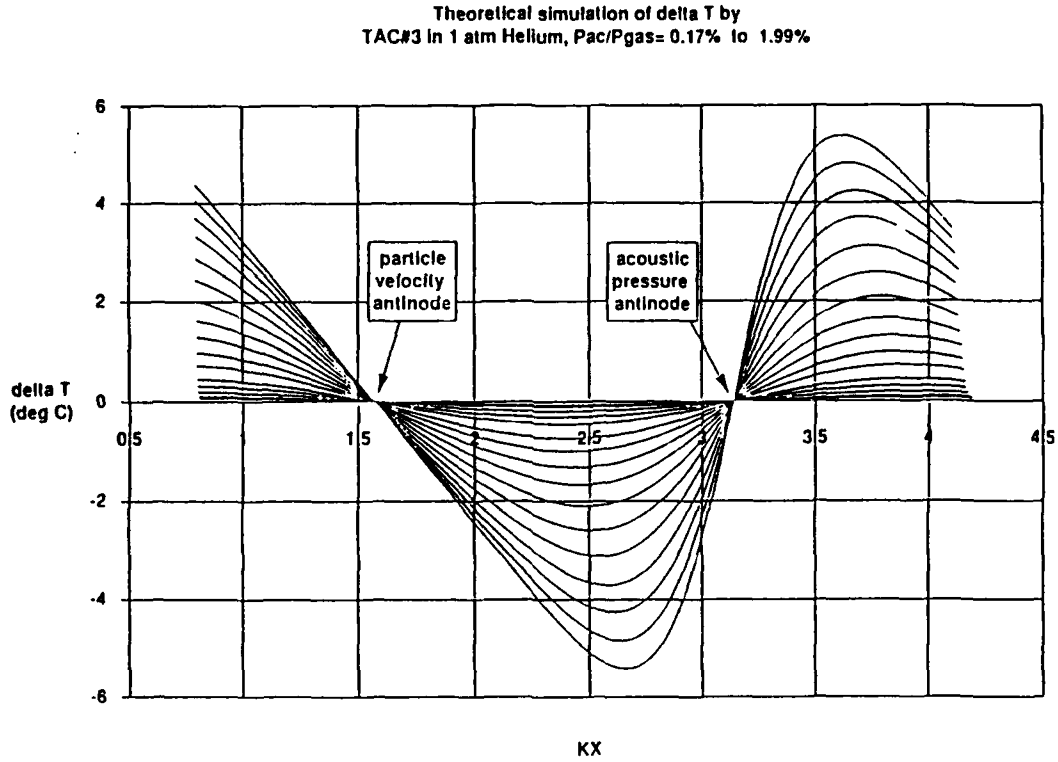

Figure 3

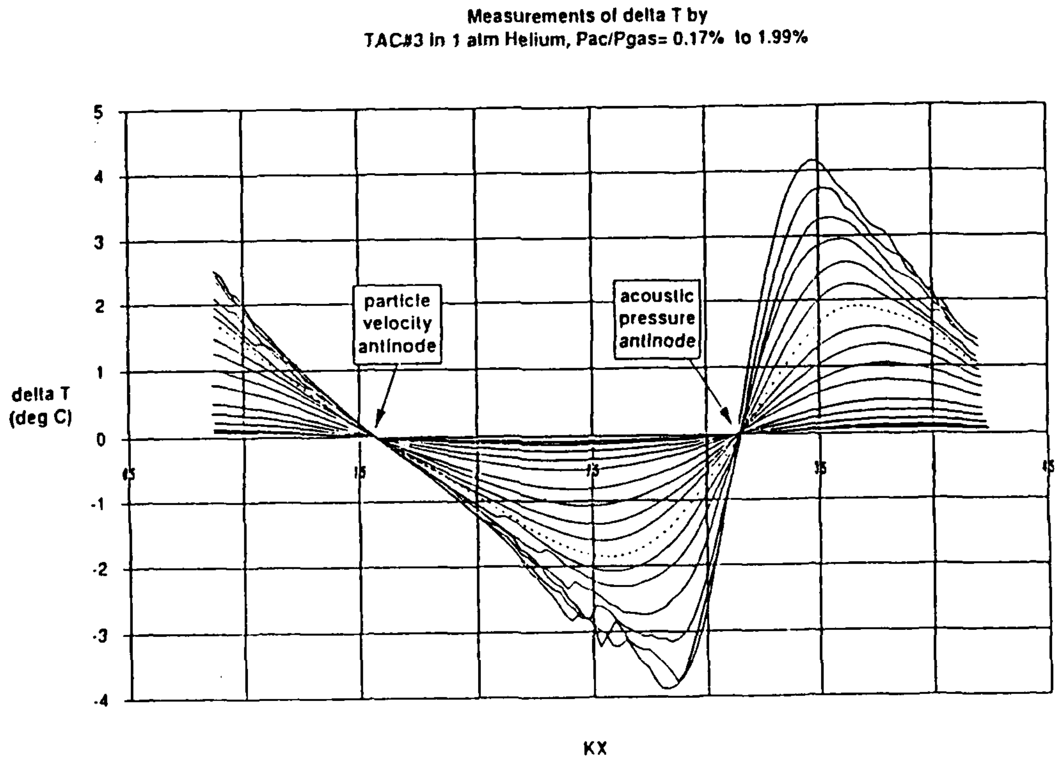

Figure 4

All ratios have approximately the same value for drive ratios less than approximately 0.4%. The ratios then start to decrease in a more-or-less linear fashion for drive ratios between approximately 0.4 to 1.0%. At this point the quasilinear decrease stops. It should be pointed out that the data for the drive ratio of 1.03% correspond to the dashed curve in Fig. 4 which demarcates the regions of regular and irregular behavior. As the drive ratio increases beyond approximately 1.0%, the pressure antinode slope ratio increases slightly and then levels off at a drive ratio of approximately 1.5%. In the drive ratio region above 1..0%, the temperature difference ratio more-or-less levels off, whereas the velocity antinode slope ratio tends to decrease, though at a slower rate than in the 0.4 to 1.0% drive ratio region.

Measurements were made with three different TACs in helium and argon for mean gas pressures between approximately 100 and 300 kPa. In general, all the data follow the same pattern as discussed above, which can be summarized as follows. At low values of the drive ratio (below approximately 0.4%) the measurements agree well with predictions. The data series of the temperature difference changes from a sinusoid to a sawtooth as predicted. As the drive ratio increases from 0.4% to approximately 1.0%, the agreement between measured and predicted results decreases almost linearly with increasing drive ratio. The data series continues to distort, yet remains smooth. At drive ratios greater than approximately 1%, the data series of the measured temperature difference becomes irregular and the linear dependence on drive ratio stops. At the highest drive ratios, the ratio of the measured results to the predicted results is more or less independent of drive ratio, although some exceptions were found. Finally, measured values of the temperature difference agree very well in the vicinity of the pressure antinode regardless of drive ratio.

Several conclusion may be drawn from this work. The first conclusion is that the thermoacoustic effect is well understood at low values of the drive ratio. The second conclusion is that there are two distinct regions of behavior at higher drive ratios. One region, which occurs for drive ratios less that approximately 1%, is characterized by a linear decrease in the agreement between theory and experiment. The second region, which occurs for drive ratios greater than approximately 1%, is characterized by the onset of irregularities in the temperature difference data series. Also the linear dependence of the disagreement disappears. Further, because the agreement is always good in the vicinity of the pressure antinode (velocity node), some velocity dependent effect may be the cause of the poor agreement at higher drive ratios. This conclusion is also supported by the observation of the sudden onset of irregularities in the data series.

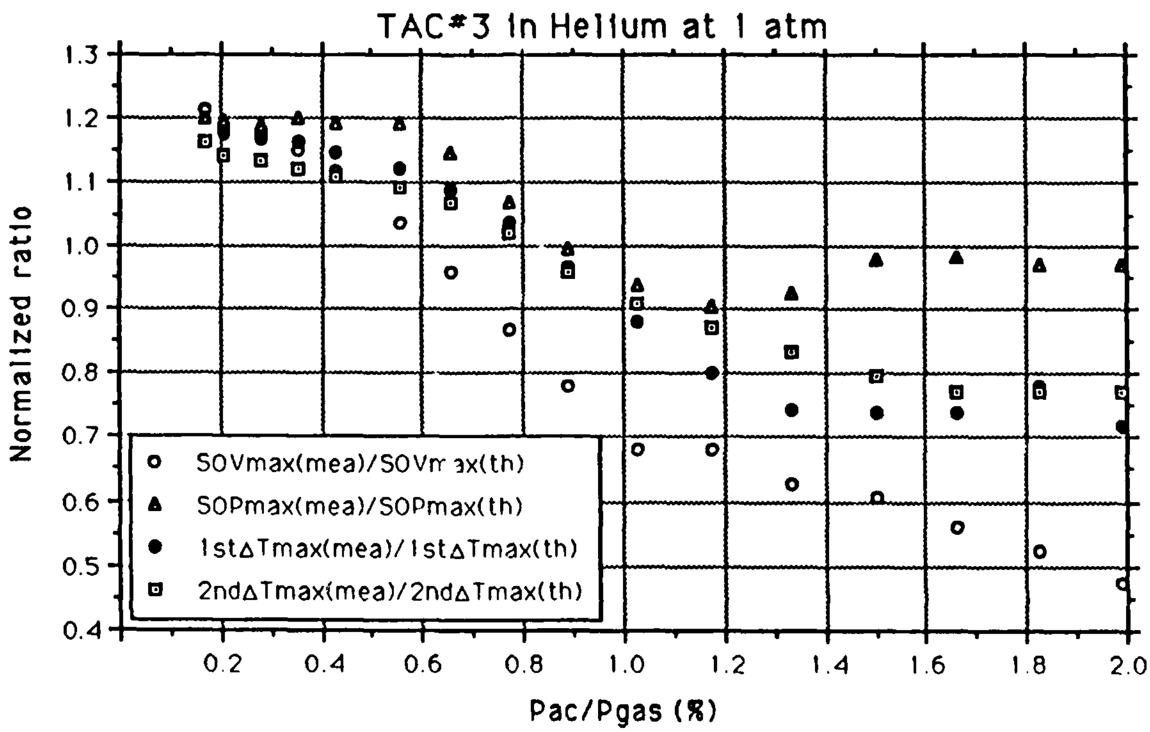
TAC#3 in Helium at 1 atm
Normalized ratio
Pac/Pgas (%)
SOVmax(mea)/SOVmax(th)
SOPmax(mea)/SOPmax(th)
1st∆Tmax(mea)/1st∆Tmax(th)
2nd∆Tmax(mea)/2nd∆Tmax(th)

Figure 5

2. Heat Driven Prime Movers and Heat Pump

In 1989, we began an investigation of heat driven thermoacoustic prime movers and heat pumps. This study is a continuation of the work in which John Wheatley was involved at the time of his death. Much of the apparatus for this project was designed and used by Wheatley. The ultimate goal is to fully understand the operation of heat driven heat pumps.

The general approach is based on the concept that the work output of a thermoacoustic engine alters the net absorption coefficient of the engine/resonator system. Therefore, the work output can be determined by measuring the net absorption coefficient of the system, which can be inferred by measuring the quality factor (Q) of the engine/resonator. The results of the measurements are compared to basic thermoacoustic theory developed by Swift.[2] The Q is measured as a function of the externally imposed temperature gradient. As the temperature gradient across the prime mover stack is increased, the net absorption in the system decreases (the Q increases). At some point the critical temperature gradient is reached and the net absorption coefficient is zero (the Q will be infinite). A further increase in the temperature gradient results in a negative net absorption, which can be interpreted as the ability of the engine to do net useful work, either as a prime mover or a heat pump. Tracking the work output of the engine as a function of the applied temperature gradient allows us to detect any point of departure of theory from experiment. The development of the prime mover and heat pump are incremental. The first step is to understand the absorption in the resonator, after which components of the prime mover and heat pump will be added and investigated piece by piece until the final form (heat driven heat pump) is achieved.

The initial investigation of the resonator has been completed. A cylindrical resonator was chosen on the basis that the properties of the acoustic field within it can be easily calculated. The Q has been measured with the resonator filled with both helium and argon at a variety of pressures up to 500 kPa. In general, the measured Q agrees with theory to within better than 10%.

Following these measurement, we installed one heat exchanger and repeated the same set of measurements. The results of a simple calculation of the Q agree with the measured Q to within about 10%. However, a more detailed calculation still needs to be performed before the true comparison is known.

The experiment has progressed to the prime mover stage. We have installed the prime mover stack and the hot heat exchanger and started a series of measurements of Q as a function of mean gas pressure and temperature gradient across the prime mover stack. There are two regions of behavior to be investigated. The first region is that in which the

temperature gradient is less the critical gradient, in which the work output of the prime mover is not sufficient overcome the other losses in the system. The second region is that in which the temperature gradient is greater than the critical gradient. In this region, the prime mover generates sound (net useful work).

Presently, we are making measurements in the first region. The experimental technique has proven reliable and the measurements reproducible. No major difficulty is anticipated with the measurements. The next major hurdle to overcome is the theoretical computation. Although Swift's theory includes an expression for the work output generated by a thermoacoustic engine,[2] it offers no direct comparison with the Q measurements. One approach for making the comparison is to use the relationship that the Q is directly proportional to the ratio of the energy stored in the system to the energy lost per cycle. The theory provides an expression for the energy lost (or gained) per cycle. All that remains is to calculate the energy stored in the system. This calculation is complicated by the presence of the prime mover stack, heat exchangers, and non-negligible temperature gradients. It is expected that the prime mover measurements and calculations will be completed by December.

Once the prime mover investigated is completed, another stack and heat exchanger will be introduced into the engine to convert it into a heat pump. A similar sequence of measurements will be repeated.

3. Visualization of Thermoacoustic Heat Transport

The projects described above involve macroscopic thermoacoustics, in the sense that the measured quantities are the average temperature difference across a TAC or the average net absorption coefficient in a resonator. However, the theory of thermoacoustic heat transport is a microscopic, boundary layer, theory. In order to apply this theory to our experiments, it is assumed that all part of the stacks behave in the same manner, that edge effects and other complicating factors do not exist. One way to investigate whether or not these complications play any significant role in our experiments is to find a method to "visualize" the thermoacoustic process and see if these assumptions are valid. This notion involves a completely different measurement technique. Two methods of visualizing thermoacoustics are apparent.

One technique is to utilize a thermal imaging camera in order to photograph, in the infrared, a plate or stack of plates exposed to an acoustic standing wave. The result will be a real time image of the evolution of the temperature gradients in the plate and should yield

information about thermoacoustic heat transport which can not be gained using discrete thermocouples. This experiment will necessitate fitting a resonator (similar to the one used in the TAC measurements) with an infrared transparent window. The resolution of the camera (currently available in the Electro-optics laboratory in the NPS Physics Department) is 0.2 °C, which is sufficient for qualitative measurements. The biggest disadvantage is the image size that can be produced with the lenses with which the camera is presently equipped. These lenses are intended for imaging larger objects. However, they are sufficient for preliminary measurements. If the technique shows promise, a better suited lens can be acquired in the future.

The second technique, though less sophisticated, is easier to implement and can yield equally useful qualitative information. In this method, strips of liquid crystal, temperature sensitive, sheets replace, for instance, the plates of a TAC. When these strips are exposed to a large amplitude acoustic standing wave, a visible color gradient is setup in the strip. We have constructed a transparent, Plexiglas resonator in which to conduct the experiment so that the strips are readily visible.

The strips that are in use have a 3 °C temperature range over which the color changes from brown to green to blue as the temperature increases. One disadvantage to the method is that the ambient temperature must be within the temperature range of the strip. Under ideal conditions, the ambient temperature should be at the midpoint of the temperature span. When these conditions are present, the strip is a uniform greenish color in the absence of a sound field. When a standing wave is setup, the color change occurs quickly. Within a few seconds, the edge of the strip closest the nearest pressure antinode turns blue, while the other edge turns brown. As time progresses, the blue and brown regions expand toward the center of the plate, forming a uniform temperature gradient across the strip. Eventually, the mean temperature of the plate rises and the overall color pattern shifts towards blue. Finally, the entire strip is dark blue, indicating that the temperatures are out of the temperature range of that particular strip.

There are several important results arising from these preliminary experiments. The extreme edges change color first, demonstrating the fact that the transported heat accumulates at the edges of the plates first. A uniform gradient is established only after thermal conduction acts to destroy this initial temperature gradient. These observations are entirely consistent with the present understanding of thermoacoustics. A final, yet not unexpected, result is that mean temperature of the plate increases.

Although, we have made only preliminary investigations with the liquid crystal method of visualizing thermoacoustics, the method has already yielded useful qualitative information. Aside from these benefits, this technique is very useful for demonstrating

thermoacoustics. Seeing a reading on a voltmeter change is one thing, seeing the color of a plate change is quite another.

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PUBLICATIONS / PATENTS / PRESENTATIONS / HONORS REPORT

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PAPERS SUBMITTED TO REFEREED JOURNALS
(Not yet published.)

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PAPERS PUBLISHED IN REFEREED JOURNALS

Anthony A. Atchley and Andrea Prosperetti, "The crevice model of bubble nucleation", J. Acoust. Soc. Am. **86** (3), 1065-1084 (1989). (Supported by a previous ONR Contract, The F. V. Hunt Postdoctoral Fellowship, NPS Research Foundation, and NSF.)

PAPERS PUBLISHED IN NON-REFEREED JOURNALS

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TECHNICAL REPORTS PUBLISHED

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BOOKS (AND SECTIONS THEREOF) SUBMITTED FOR PUBLICATION

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Anthony A. Atchley and Lawrence A. Crum, "Acoustic Cavitation and Bubble Dynamics", in Ultrasound: Its Chemical, Physical, and Biological Effects, edited by K. Susslick (VCH Publishers, New York, 1988), Chap. 1, pp. 1-64. (Supported by a previous ONR Contract and NIH.)

PATENTS FILED

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INVITED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

Thomas, J. Hofler, Anthony A. Atchley, and Steven L. Garrett, "Simple demonstration of a thermoacoustic sound source", J. Acoust. Soc. Am. 85, Suppl. 1, S112(A) (1989). Presented at the 117th Meeting of the Acoustical Society of America, Syracuse, NY, May 22-26, 1989.

CONTRIBUTED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

Anthony A. Atchley, T. J. Hofler, and M. D. Kite, "Acoustically generated temperature gradients in short plates", J. Acoust. Soc. Am. 84, Suppl. 1, S36(A) (1988). Presented at the 116th Meeting of the Acoustical Society of America, Honolulu, HI, November 14-18, 1988.

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